DEVELOPMENT OF A MILLIMETER WAVE MASER

Report No. 3

Contract No. DA 36-039-SC-90778

Project No. AAD 51032

Third Quarterly Progress Report,
1 December 1962 to 28 February 1963

U.S. ARMY ELECTRONIC RESEARCH AND
DEVELOPMENT LABORATORY
Fort Monmouth, New Jersey

WESTINGHOUSE ELECTRIC CORPORATION
Air Arm Division
Baltimore, Maryland

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The objective of this program is to perform research and development directed toward the design of a broadband, low noise, maser amplifier operating near 70 gc.

Prepared by

W.E. Hughes
R.A. Moore

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1. PURPOSE

The purpose of this program is to perform research and development directed toward the construction of a maser amplifier operating near 70 gc. The design goals are to obtain a broadband, low noise amplifier which will be simple to operate and easily tunable over a considerable frequency range. To this end, studies will be carried out to determine the most suitable maser material and pumping method.

Also, various broadbanding techniques will be studied, and where a method shows promise, experiments using this technique will be conducted.

2. ABSTRACT

Preliminary design parameters have been established for a traveling-wave configuration of the 70 gc maser. The feasibility of using a traveling-wave structure depends critically upon the availability of a suitable isolation material and upon the development of microwave matching techniques. Several ferrite isolator materials have been tested as a function of resonant frequency versus magnetic field at room temperatures and at liquid helium temperatures.

Rutile maser materials, having a very high dielectric constant, are difficult to insert into the microwave circuitry without causing very large mismatches. Therefore, the design of proper matching devices and configurations has been of primary concern during this period.

A computer program was established during this period to solve the steady state rate equations for the iron ion in rutile. Since the relaxation rates are not known with sufficient accuracy, the results of the program are somewhat inconclusive.

3. PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

A conference was held at the Westinghouse Air Arm Division, Baltimore, Maryland, on 30 January 1963, attended by Mr. Emerson Frost of the United States Army Electronic Research and Development Laboratory (USAELRDL) and Mr. W.E. Hughes of Westinghouse. The conference was held to discuss the progress being made on the contract, and to establish some of the final design parameters of the 70 gc maser.

On 12 February 1963, Dr. R.A. Moore and Mr. D.C. Webb of Westinghouse visited Fort Monmouth, New Jersey, to confer with E. Frost, I. Bady, T. Collins, and W. Wade of USAELRDL on the nonreciprocal transmission portion of the traveling-wave maser program.

4. FACTUAL DATA

4.1 SUPERCONDUCTING MAGNET

During this period, the design parameters for the superconducting magnet have been sufficiently established to allow construction to begin.

The magnet is designed to produce a magnetic field variable from 4 to 5.5 kilogausses by an external adjustment. The field will be uniform to within ±2 gausses over a length of 1-1/2 inches. The superconducting wire will be wound over an iron bobbin and the spacing between the pole faces will be 0.220 inch. Since a uniform high field is desired, it will be necessary to polish the pole faces to an optical flatness of a few microns.

The magnet will be provided with a persistent mode switch which will allow all external power to be disconnected after the proper field has been established.

Figures 1, 2, and 3 show the preliminary design of the helium dewar, TWM magnet, and waveguide assembly that will be used. It is anticipated that the magnet will be delivered to the Air Arm Division of Westinghouse for testing in the first week of April. There will be approximately three months of testing before delivery of the maser to the Signal Corps.

4.2 MICROWAVE MATCHING MEASUREMENTS

Because of its high dielectric constant, rutile is very difficult to place in a microwave circuit without creating high standing wave ratios by reflection at the surfaces of the material. In the traveling-wave structure, any signal power that is reflected back toward the antenna will be lost to the receiver and will have the effect of increasing the noise figure of the receiving system. Since the maser is useful because of its low noise figure, any mismatch that causes signal power to be lost, cannot be tolerated.

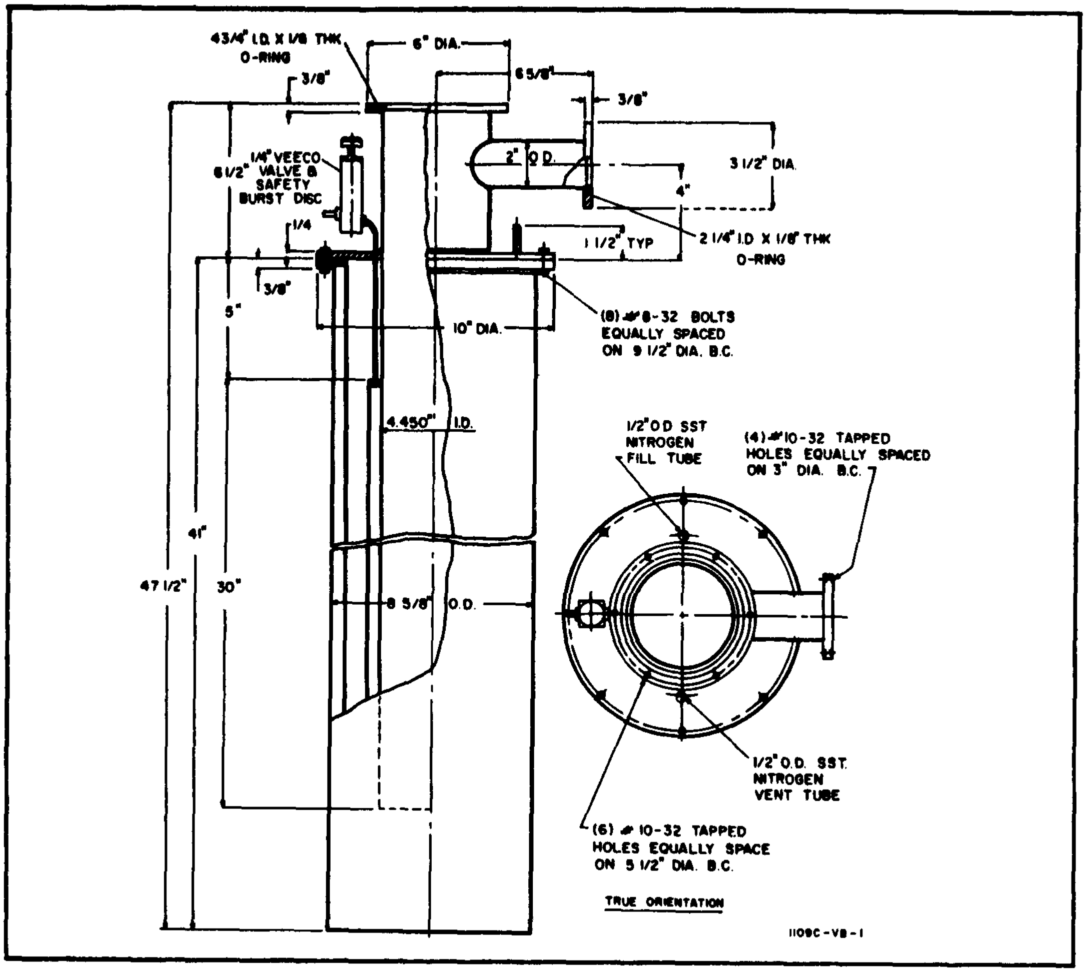

Figure 1. Dewar for Superconducting System

One of the major efforts in designing the traveling-wave maser must be directed toward proper matching of the maser material to the microwave circuit.

The matching should be done in such a manner that, with no external magnetic field applied, the maser crystal will appear transparent to the signal freguency and at the same time it should appear as a matched load to the pump source.

First attempts to match the rutile maser sample to the microwave circuit were made using V-band (50-75 gc) waveguide, completely filled by a

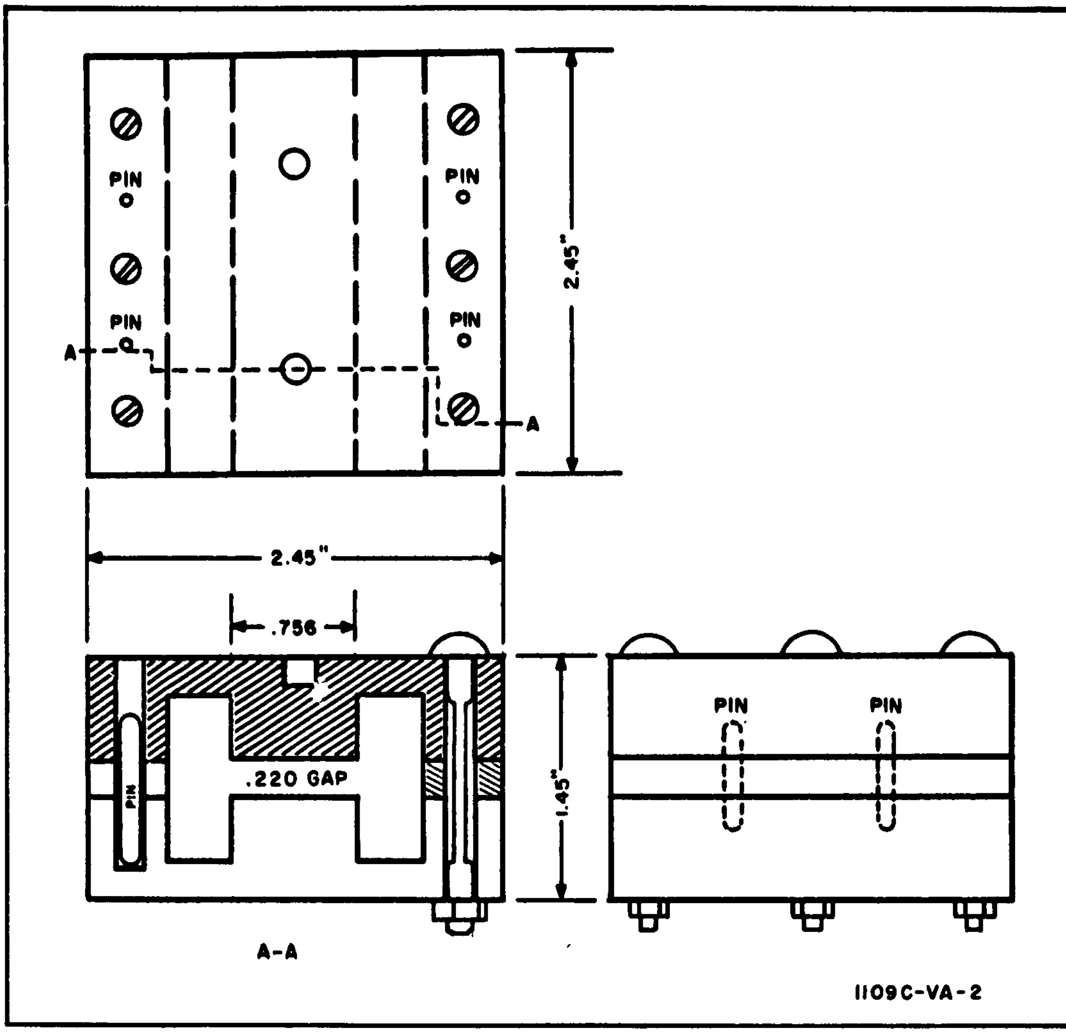

Figure 2. Iron Bound TWM Magnet

crystalline rutile sample. Matching was accomplished by placing a quarter-wave piece of Stycast with a dielectric constant of 13 on both ends of the rutile.

A long tapered section of Teflon was used as a dielectric transition from the waveguide to the Stycast. By placing the sample in the proper position in the waveguide, the signal loss through the assembly could be made as low as 5 db for a 1-1/4-inch long sample. When the assembly was cooled to

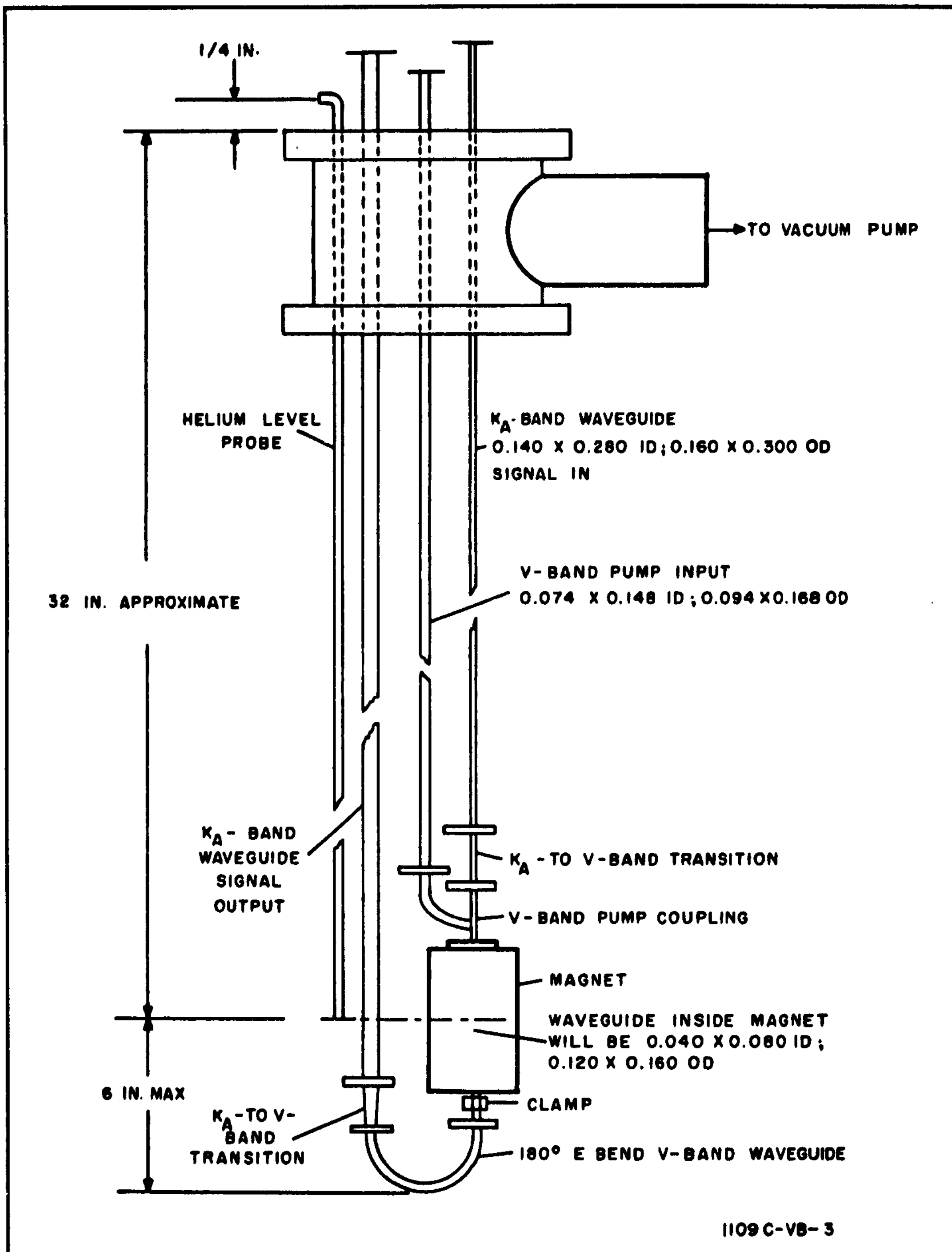

Figure 3. 70 gc Maser Waveguide Assembly

liquid helium temperatures a great number of dielectric resonances were set up in the sample, indicating that the matching was far from optimum. Also, there was a large amount of signal power reflected from the sample which further indicated a poor match.

A second approach to the matching problem was made by placing a sample of rutile in W-band (90-140 gc) waveguide and using Stycast and Teflon matching devices as in the V-band waveguide. The losses to the signal frequencies were approximately 5 db and a large reflected signal indicated a poor match to the rutile sample.

The third approach, the one that appears most applicable to date, has been to use a very thin slab of rutile, 0.015 to 0.020-inch thick, placed along one wall of the V-band waveguide. First tests of this approach showed that dielectric resonances were still being established in the sample; however, the transmission losses were on the order of 2 db and coupling to the sample appears to be good at both pump and signal freguencies.

A piece of rutile is now being formed that will be 0.010 inch thick and 1-1/8 inches long. This sample will be bonded to Rexolite and tapered on each end to a form very sharp leading and trailing edge.

To this new structure of Rexolite and rutile will be added a thin layer of ferrite isolator material and these three materials will form a sandwich which will be placed along one wall of the V-band waveguide. Since the structure is being formed at the Westinghouse Research Laboratory, it is anticipated that testing will be started about the second week in March.

4.2.1 Matching Techniques

In order to optimize noise and gain characteristics, it is necessary to minimize generation of higher order modes. A first attempt to do this was made by completely filling the cross section of the waveguide since if the cross section is uniform, none of these modes will be generated.

In order to suitably match to the rutile sample, the scheme shown in figure 4 was employed. The tapered Teflon pieces were used to provide a better impedance match with the immediately available intermediate

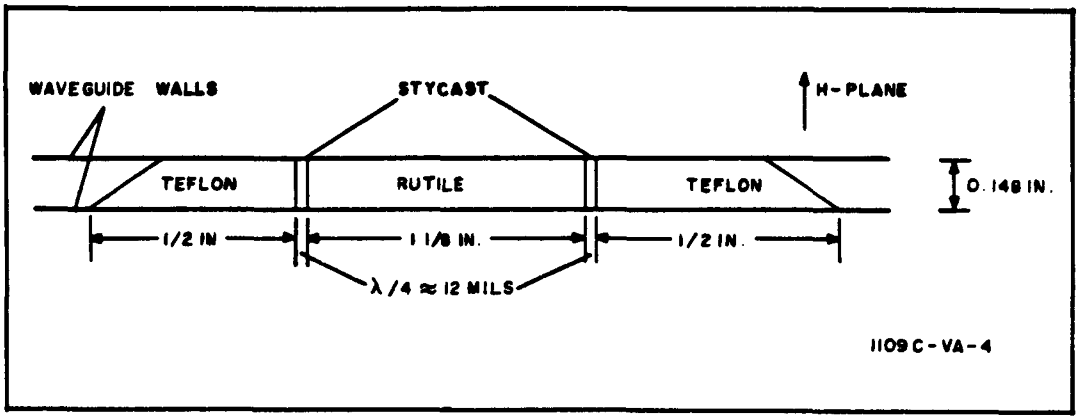

Figure 4. Rutile Sample With Matching Sections

dielectric constant materials than could be obtained without it. Furthermore, the Teflon served to hold the matching sections firmly in place.

To minimize reflections, the impedance of the matching section should be the mean of the impedances of the two materials being matched, in this case, Teflon and rutile. The dielectric constant should equal $\sqrt{\epsilon_r \times \epsilon_t}$, ≈ 14, where ϵ_r and ϵ_t are the dielectric constants of rutile and Teflon respectively. In the present experiment, Stycast having a dielectric constant of about 3.5, was used. The sections should be a quarter-wavelength long in the medium at the desired frequency, which at 70 gc is about 12 mils. Although this configuration is theoretically matched at only a single frequency, it should be adequate for the range of frequencies of the present application. If it does not prove to be so, additional matching sections can be used.

The Teflon-rutile configuration had an insertion loss ranging from 4 to 7 db over frequencies from 67 through 73 gc. Although the loss is considerably less than that of previous configurations, for there still appears to be a significant amount of multimoding. The large number of dielectric resonances observed at liquid helium temperatures tend to further verify this conclusion.

In order to get sufficient interaction with the ferrite, the width of the rutile must be substantially reduced. (This is elaborated on later in this report.) The presence of the ferrite slab in this configuration will greatly enhance the possibility of higher order mode generation. To eliminate this problem, a dominant mode structure will be employed. The rutile widths required may be quantitatively determined from figure 5.[1] At 70 gc, with the dielectric in the center of V-band waveguide, a sample width of 5 mils would be required in order that all higher order modes be cut off. If a smaller waveguide (for example, W-band waveguide) is used, the sample width can be increased to 10 mils with the structure still being dominant mode. A further improvement can be realized by placing the rutile at the edge of the guide. Here the TE_{20} mode effectively becomes the dominant mode of a guide of dimensions 2a and 2c total width and dielectric width respectively. The TE_{40} mode thus becomes the first higher order mode. By using this configuration in the W-band waveguide, the dielectric width could further be increased to 12 mils.

Suitable matching will be attained by using quarter-wave sections of Stycast. The optimum width of these sections will be experimentally determined. The configuration which will be used to study the properties of a dominant mode structure is shown in figure 6.

4.2.2 Nonreciprocal Attenuation

In order to determine a suitable composition of $SrO \cdot x\,Al_2O_3\,(6-x)\,Fe_2O_3$ to provide suitable nonreciprocal attenuation, transmission cavity measurements were made on spheres of several different compositions.

In order to determine the temperature dependence of the anisotropy field, material was obtained having x = 0 and x = 0.5 from Dr. I. Bady of USAELRDL. From these results it was deduced that a value of x = 0.2 would be required for the present application.

Since this composition was unavailable from this source, material was obtained from Dr. Paul Albert of the Westinghouse Research Laboratories and Dr. Frank Brockman of the Philips Laboratories.

1 P. H. Vartanian, W.P. Ayres, and A. L. Helgesson, "Propagation in Dielectric Slab Loaded Rectangular Waveguide," PGMTT of IRE, MTT-6, (April 1958), 215-222.

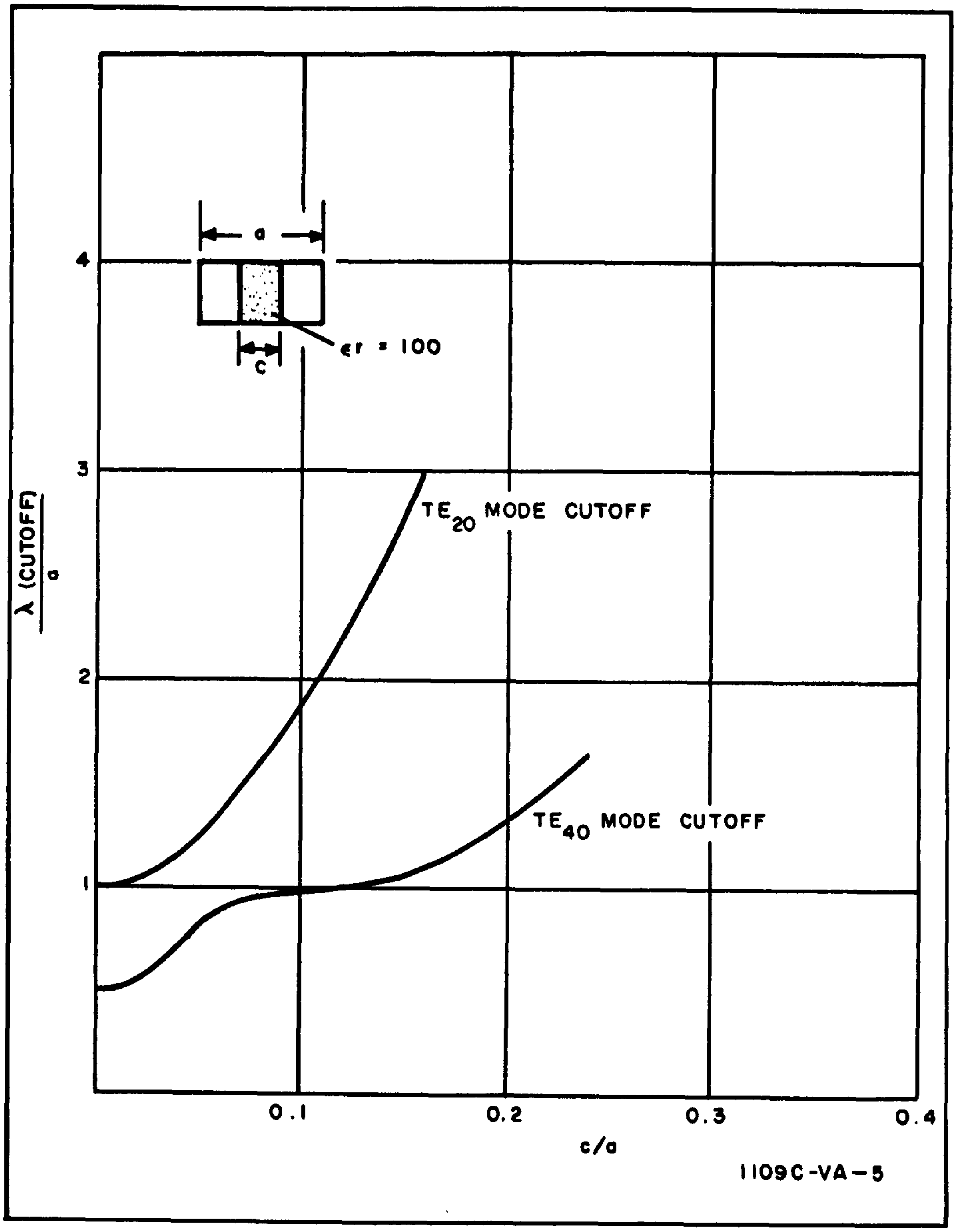

Figure 5. Normalized Cutoff Wavelength as a Function of Dielectric Width ($\epsilon_r = 100$)

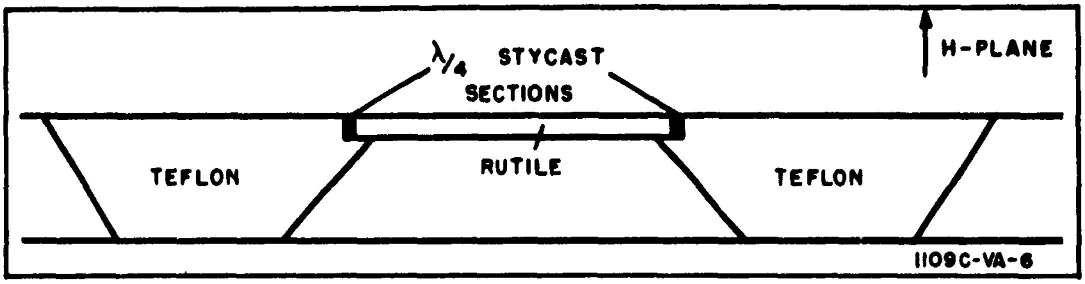

Figure 6. Proposed Traveling-Wave Configuration

The results of the dispersive measurements are indicated in figure 7. A curve of the field versus frequency relationship as required by maser energy level considerations is also indicated. Corrections for demagnetizing factors and temperature dependence have been included. The amount of shift with temperature was based on the observed change of anisotrophy of the x = 0 and x = 0.5 materials and was taken to be 0.6 kilogauss. Since a means of tuning the cavity at liquid helium temperatures has now been incorporated into the structure, it will now be relatively easy to measure the dispersion over the required range of frequencies.

The Philips material, $SrO \cdot 0.2\ Al_2O_3\ 5.8\ Fe_2O_3$, appears to be adequate for the present application. Although the curves of ferrite dispersion and required maser dispersion have opposite slopes, the ferrite linewidth is sufficiently broad, about 2 kilogausses, that it still should be possible to obtain adequate attenuation over the entire frequency band, 69-71 gc.

When the width of the rutile is an appreciable fraction of a wavelength (in the medium), the magnitude of fields is so small and their decay so rapid at the edge that interaction with any ferrite placed at that point is slight. In order to determine the rutile width necessary to obtain a sufficient amount of nonreciprocal attenuation for the present application, a perturbation analysis was conducted. The configuration treated is shown in figure 8.

It is assumed that the H-fields are circularly polarized throughout the ferrite region, all losses result from magnetic losses in the ferrite and the

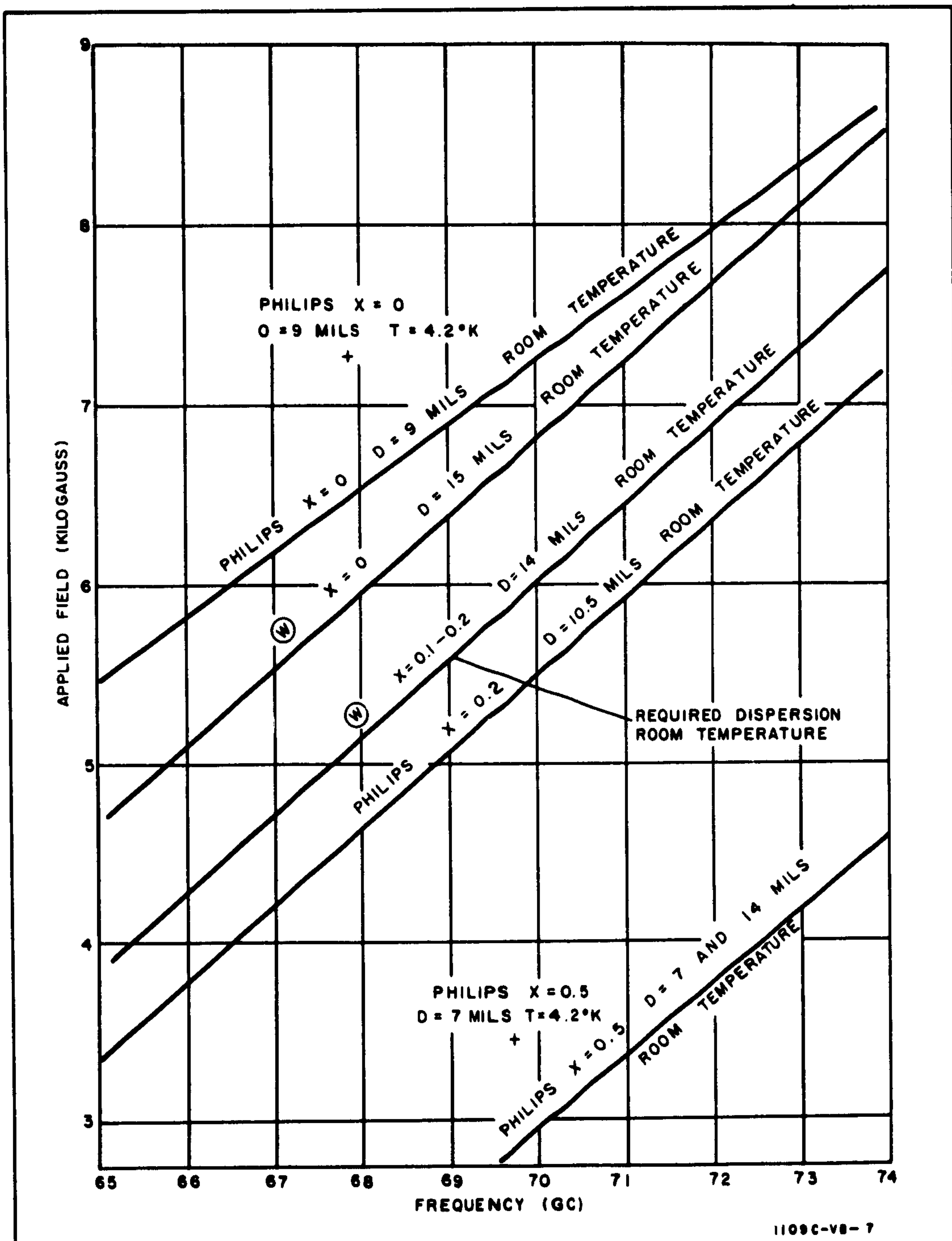

Figure 7. Dispersive Measurements of $SrO \cdot xAl_2O_3(6-x)Fe_2O_3$

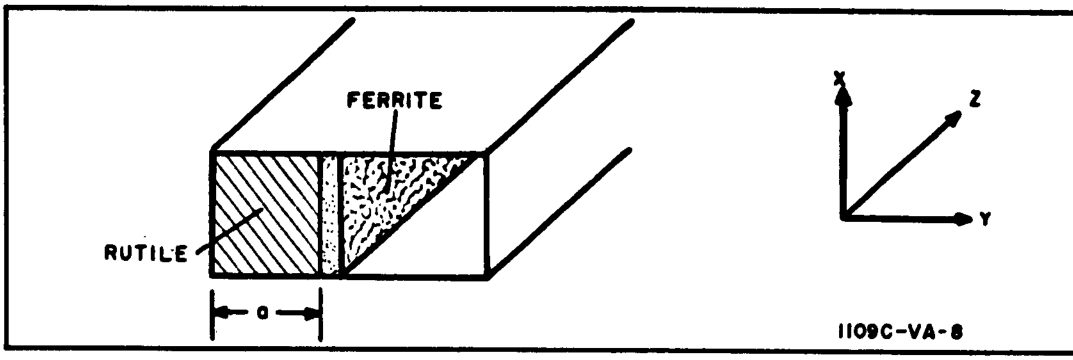

Figure 8. Configuration Used in the Isolator Perturbation Analysis

real (loss) portion of the propagation constant is much less than the imaginary portion. All assumptions prove to be quite valid in this treatment. The attenuation constant is given by the expression

$$\alpha = \frac{PL}{2\,PT} = \frac{\omega\,\mu_0\,x''}{2}\;\frac{\int_{ferrite} H^2\,da}{\int_{total} E \times H^* n \cdot ds} \tag{1}$$

which reduces to

$$\alpha = \frac{\omega^2 \mu\,\epsilon}{\beta_g}\left(\frac{4\pi M_s}{\Delta H}\right)\frac{\int_{ferrite} H_a^2\,da}{\int_{total} H_a^2\,da} \tag{2}$$

By substituting the appropriate expressions[2] into equation 2

$$H_{rutile} = D \sin Ur \tag{3a}$$

$$H_{ferrite} = D \sin U\, e^{V(1-r)} \tag{3b}$$

$$\beta_g = \sqrt{\frac{\mu_0}{\epsilon_0}}\sqrt{\frac{U^2 + V^2}{\epsilon_f U^2 + \epsilon_r V^2}} \tag{3c}$$

2 R. A. Moore and R. E. Beam, "A Duo-Dielectric Parallel-Plane Waveguide," Proceeding of the National Electronic Conference, (1956), 689-705.

the equation for attenuation may be written

$$\alpha = \frac{2\pi}{\lambda_0} \left(\frac{4\pi\, \mu_s}{\Delta H}\right) \sqrt{\frac{\epsilon_f U^2 + \epsilon_r V^2}{U^2 + V^2}} \; \frac{\dfrac{\sin^2 U}{V}}{1 - \dfrac{\sin 2V}{2U} + \dfrac{\sin^2 U}{V}} \tag{4}$$

where $r = \lambda/a$ and U and V are the separation constants as determined from Maxwell's equations. If $SrO \cdot 2\, Al_2O_3\, 5.8\, Fe_2O_3$ is used ($\Delta H = 2\, K_g$, $4\pi\, M_s = 3.5\, K_g$) as the ferrite material, a rutile width of 26 mils will provide 20 db of attenuation in a 1-1/2 inch length at 70 gc. This analysis is applicable to the configuration shown in figure 6. The side wall opposite the rutile will have a negligible effect on the fields since they decay very rapidly away from the sample. For the 26-mil width, this is about 3 db/mil.

The above technique was tested by applying it to an H-waveguide resonance isolator for which experimental results were available. The theoretical calculations yielded a reverse attenuation of 30 db as compared to the reported experimental value of 27 db.[3]

It thus appears that the 26-mil width of rutile would result in adequate attenuation for this application. The width to assure a dominate mode was found to be 12 mils. However, a dominant mode structure may not be strictly necessary.

It appears that a 26-mil width of rutile with a slab of ferrite a few mils thick would provide adequate attenuation for this application. The requirement that the structure be dominant mode is thus much more severe than the attenuation requirement. If a nondominant mode structure were allowed, it is conceivable that all higher order modes would interact sufficiently with the ferrite that any resonant effects would be eliminated. However, from noise and loss considerations, it would still be desirable to use a dominant mode structure.

3 W.W. Anderson and M.E. Hines, "Wide Band Resonance Isolator," PGMTT of the IRE, MTT-9, (January 1961), 63-67.

4.3 MILLIMETER WAVE TRANSMISSION

It will be noted in figure 3 that the final maser design will use oversize waveguide to transmit the signal energy to and from the active maser material. This has been done for two reasons; (1) the thin wall stainless steel waveguide at V-band has small ripples along its length which set up high impedance modes to some frequencies within the signal frequency bandwidth, which may be eliminated by the oversize waveguide, and (2) an oversize waveguide is less lossy than dominant mode waveguide if the wave is properly launched. [4]

During this period a few very preliminary measurements of loss per unit length for dominant versus oversize waveguide were made which indicated a loss of approximately 1 db/ft in V-band waveguide and 0.45 db/ft in K_a-band waveguide. Thus, these measurements indicate that it would be beneficial to use the oversize waveguide approach in the final system if the waveguide run is longer than 2 feet.

One other solution to the transmission losses at 70 gc would be to use circular waveguide throughout the receiving system. Since extreme care must be used to avoid setting up lossy modes, it was felt that circular waveguide would be too difficult to use in an experimental setup and this approach has been abandoned.

4.4 COMPUTER CALCULATIONS

During the period of this report, the Westinghouse IBM 7090 computer facilities were used in an attempt to discover the necessary relaxation rate ratios to allow the 70 gc maser to operate with a pump frequency of 118 gc. It was necessary to use the computer because, for the iron ion in rutile there are six energy levels available in the lowest levels and to be correct, the solution must consider the population densities of all six levels. Although only the 1st, 5th, and 3d levels are actually used in the maser operation,

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4 G. R. Valenzuela, "Millimeter Transmission by Oversize and Shielded-Beam Waveguides," <u>The Millimeter and Submillimeter Conference Program and Digest</u>, (January 7 through 10, 1963), 7.

the 2d, 4th, and 6th cannot be neglected and a simple three level type solution is not sufficient.

The computer was programmed to solve the following set of equations in the steady state i.e., $\dot{n}_i = 0$ for the values of n_1, n_2, n_3, n_4, n_5, n_6 when the values of the ω_{ij}, W_{ij}, and N were given.

$$\dot{n}_i = \sum_{ij} (\omega_{ji} n_j - \omega_{ij} n_i) + \sum_{ij} W_{ij} (n_i - n_j) \qquad \begin{array}{l} i = 1, 2, 3, 4, 5, 6 \\ j = 1, 2, 3, 4, 5, 6 \\ i \neq j \end{array} \qquad (5)$$

$$N = n_1 + n_2 + n_3 + n_4 + n_5 + n_6$$

In all cases the Boltzmann's factor

$$\omega_{ij} = \omega_{ji} e^{\frac{h\nu_{12}}{kT}}$$

was used, and all $W_{ij} = 0$ except W_{15} and W_{51}. In these equations ω_{ij} is the transition probability between the ith and jth levels, W_{ij} is the radiation induced transition probability, N is the total number of spins involved, h = Planck's constant, k = Boltzmann's constant, ν_{ij} is the transition frequency, and T is the bath temperature.

Various values for the ω_{ij}'s were chosen and the machine was asked to find the value of ν_{53} that would allow n_5 to be greater than n_3.

Many solutions were found for the equations, however the only conclusion that could be drawn was that the transition rate ω_{12} needs to be almost an order of magnitude greater than other transition probabilities for the 70 gc maser to operate. The main difficulty with the solutions was the fact that none of the rates are known to the accuracy necessary for conclusive results.

Since the scope of the present program will not allow measurement of the relaxation rates, further work along these lines is not justified.

5. CONCLUSIONS

Tests carried out during this period have shown that a traveling-wave-type maser is feasible at 70 gc. Further work is needed to properly match the rutile sample to the microwave circuit and to obtain a proper isolator material.

A computer program for the solutions to the steady state rate equations has shown that a much more detailed knowledge of the transition rate will be required before a completely satisfactory explanation of the 70 gc maser operation can be given.

A new superconducting magnet design has been completed and fabrication of the device is being carried out. This magnet will supply a field of 4 to 5.5 kilogausses with a uniformity of 2 gausses over a crystal 1-1/2 inches long.

6. PROGRAM FOR NEXT INTERVAL

Since the next interval will be covered by the final report, the 70 gc maser will be completed during that period.

Final assembly and testing will be completed and the system will be delivered to USAELRDL, Fort Monmouth, New Jersey.

7. IDENTIFICATION OF KEY TECHNICAL PERSONNEL

The following is a list of personnel, their titles, and the approximate number of man-hours performed by each during the period covered by this report.

Name	Title	Man-Hours (%)
Wayne E. Hughes	Project Engineer	50
Robert A. Moore	Fellow Engineer	20
Denis C. Webb	Associate Engineer	30
Charles R. Kremenek	Associate Engineer	100

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(Contract DA 36-034-SC-90778)

Unclassified report

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2. Solid-state masers - Low noise amplifiers
3. Solid-state masers - Rutile masers

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II. Hughes, W.E.
III. Moore, R.A.
IV. United States Army Electronic Research and Development Laboratory, Fort Monmouth, New Jersey
V. Contract No. DA 36-034-SC-90778

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DEVELOPMENT OF A MILLIMETER WAVE MASER, by W.E. Hughes and R.A. Moore. Rept. for 1 Dec 62 - 28 Feb 63 on Proj. No. AAD 51032. 36 p. incl. illus. 4 refs. (Third Quarterly Progress Report, No. 3)
(Contract DA 36-034-SC-90778)

Unclassified report

Preliminary design parameters have been established for a traveling-wave configuration of the 70 gc maser. The feasibility of using a traveling-wave structure depends critically upon the availability of a suitable isolation material and upon the development of microwave matching techniques. Several ferrite isolator

(over)

UNCLASSIFIED

1. Solid-state masers - Millimeter wave masers
2. Solid-state masers - Low noise amplifiers
3. Solid-state masers - Rutile masers

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II. Hughes, W.E.
III. Moore, R.A.
IV. United States Army Electronic Research and Development Laboratory, Fort Monmouth, New Jersey
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Armed Services Technical Information Agency

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Rutile maser materials, having a very high dielectric constant, are difficult to insert into the microwave circuitry without causing very large mismatches. Therefore, the design of proper matching devices and configurations has been of primary concern during this period.

A computer program was established during this period to solve the steady state rate equations for the iron ion in rutile. Since the relaxation rates are not known with sufficient accuracy, the results of the program are somewhat inconclusive.

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